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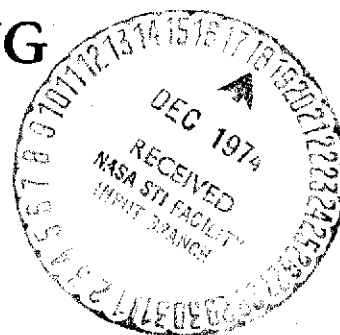
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**PERFORMANCE AND DURABILITY  
OF IMPROVED AIR-ATOMIZING  
SPLASH-CONE FUEL NOZZLES**

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# PERFORMANCE AND DURABILITY OF IMPROVED AIR-ATOMIZING SPLASH-CONE FUEL NOZZLES

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## SUMMARY

The effects of high inlet-air pressure and temperature on the durability of four designs of splash-cone fuel nozzles were investigated in an experimental combustor. Nozzle temperatures were measured, and after 56 hours of testing, nozzle erosion and susceptibility to carbon formation were observed. The most durable nozzle was selected from the durability tests and then used in determining exhaust emission characteristics for the combustor. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air total pressures of 41 to 203 newtons per square centimeter, inlet-air temperatures of 477 to 811 K, and a reference velocity of 21.3 meters per second.

The fuel nozzle designs consisted of a cylindrical-tip, a conical-tip, a blunt-tip, and a flat-tip design. The first three designs were unacceptable on the basis of durability, whereas the flat-tip nozzle operated at a reasonably low temperature and showed negligible erosion and carbon formation. Thus, it was considered acceptable from a durability standpoint. An oxides-of-nitrogen emission index of approximately 12 was obtained with flat-tip nozzles at an inlet-air temperature and pressure of 700 K and 101 Newtons per square centimeter, respectively. Emission indices for carbon monoxide and unburned hydrocarbons were 44 and 16, respectively, with flat-tip nozzles at simulated idle conditions of 477 K and 41 newtons per square centimeter. The exhaust smoke number for the flat-tip nozzles was approximately 18 at 700 K, 101 newtons per square centimeter, and a fuel-air ratio of 0.018.

## INTRODUCTION

Experimental tests were conducted in a combustor segment on four designs of air-atomizing splash-cone fuel nozzles to determine the best design on the basis of nozzle temperature, erosion damage, and susceptibility to carbon formation. In the investiga-

tion of reference 1, air-atomizing splash-cone fuel nozzles provided superior performance as compared with the other designs tested. Photographs of the sprays produced by two types of air-atomizing nozzles showed that a splash-cone design gave much better atomization than a radial-jet design. Also, in combustor tests splash-cone nozzles gave a 30-percent reduction in the oxides-of-nitrogen ( $\text{NO}_x$ ) emission index as compared with pressure-atomizing nozzles at an inlet-air temperature and pressure of 590 K and 203 newtons per square centimeter, respectively. This reduction was attributed to the fact that the splash-cone nozzle provided good atomization and spreading of the fuel spray across the combustor cross section, which tended to minimize the formation of high-temperature zones generally associated with high concentrations of  $\text{NO}_x$ .

In the present investigation, four differently shaped splash-cone fuel nozzles were mounted in a combustor segment. The nozzle designs consisted of a cylindrical-tip, a conical-tip, a blunt-tip, and a flat-tip design. The cylindrical-tip nozzle was the same design as that used in reference 1. The combustor length was 45.6 centimeters, which included the diffuser; the combustor maximum cross section was 15.3 by 30.5 centimeters. Test conditions for 56 hours of durability testing included fuel-air ratios of 0.008 to 0.018, inlet-air total pressures of 41 to 203 newtons per square centimeter, inlet-air temperatures of 477 to 811 K, and a reference velocity of 21.3 meters per second.

## APPARATUS AND PROCEDURE

### Test Facility

The combustor segment was mounted in the closed-duct test facility shown in figure 1. Combustion air drawn from the laboratory high-pressure supply system was indirectly heated to 811 K in a counterflow U-tube heat exchanger at combustor inlet-air pressures up to 203 newtons per square centimeter. The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of bypassed air. The test facility is described in more detail in reference 2.

### Test Combustor

The test combustor, shown in figure 2, was a rectangular segment which simulated an annular combustor. The overall combustor length of 45.6 centimeters included a diffuser length of 14.0 centimeters and a burner length of 31.6 centimeters, consisting

of a primary-zone length of 7.6 centimeters and a secondary-zone length of 24.0 centimeters. The combustor cross section was 5.3 by 30.5 centimeters at the diffuser inlet and 5.1 by 30.5 centimeters at the combustor exit. The maximum cross section was 15.3 by 30.5 centimeters. The inlet snout open area was 40 percent of the combustor inlet area. A detailed description of the airflow in the primary and secondary mixing zones is given in the discussion of combustor Model 3 in reference 2.

#### Fuel Injection

Jet A fuel, having an average hydrogen-carbon ratio of 0.161 and a lower heating value of 43 000 joules per gram (18 600 Btu/lb), was used in all the tests. The four differently shaped air-atomizing splash-cone fuel nozzles shown in figures 3 and 4 consisted of a blunt-tip, a flat-tip, a cylindrical-tip, and a conical-tip design. They were installed in the combustor as shown in figure 5 and simultaneously tested for durability. At a fuel-flow rate of 0.0152 kilogram per second (120 lb/hr) per nozzle, each nozzle gave a pressure drop of  $2.0 \pm 0.1$  newtons per square centimeter. Fuel nozzle temperatures were measured at the thermocouple locations shown in figure 4.

#### Instrumentation

Combustor instrumentation stations are shown schematically in figure 2, and detailed locations are given in reference 2. Inlet-air total temperature was measured at station 1 in the diffuser inlet with eight Chromel-Alumel thermocouples. Inlet-air pressure was measured at the same location with four stationary rakes consisting of three total-pressure tubes connected to differential-pressure strain-gage transducers balanced by wall static-pressure taps located at the top and bottom of the duct. Combustor exhaust temperatures and pressures and smoke samples were obtained with a traversing probe mounted at the combustor exit, station 2. The probe consisted of 12 elements: five aspirating platinum-platinum-13-percent-rhodium total-temperature thermocouples, five total-pressure tubes, and two wedge-shape static-pressure tubes. Smoke samples were withdrawn through the aspirating thermocouple lines. A detailed description of the probe is given in reference 2. The incremental travel and dwell time of the probe were controlled by automatic adjustable counters. Combustor exit temperatures and pressures were measured every 1.27 centimeters of travel for 23 locations across the combustor exhaust.

Sharp-edge orifices installed according to ASME specifications were used to measure airflow rates. Jet A fuel-flow rates were measured with pairs of turbine flowmeters

connected in series to crosscheck their accuracy. Three pairs of flowmeters were required to cover the flow range.

### Exhaust Emission Measurement

Exhaust gas samples were obtained according to the procedure recommended in reference 3. Exhaust gases were withdrawn through the air-cooled stationary probe mounted approximately 92 centimeters downstream of the traversing probe and in the center of the exhaust gas stream (fig. 1). Concentrations of oxides of nitrogen, carbon monoxide, and unburned hydrocarbons were determined with the gas-analysis equipment described in reference 1. The gas sample temperature was maintained at approximately 423 K in the electrically heated sampling line. Most of the gas sample entered the analyzer oven, while excess flow was bypassed to the exhaust system. To prevent fuel accumulation in the sample line, a nitrogen purge was used just before and during combustor ignition.

After passing through the analyzer oven, the gas sample was divided into three parts and each was analyzed. Concentrations of oxides of nitrogen, carbon monoxide, and unburned hydrocarbons were measured by the chemiluminescence, nondispersed-infrared, and flame-ionization methods, respectively. Gas samples used to determine oxides of nitrogen and carbon monoxide were passed through a refrigerated dryer and analyzed on a dry basis. Readings for oxides of nitrogen, and carbon monoxide were corrected so that they could be reported on a wet basis, as were those for unburned hydrocarbons. Emission indices for oxides of nitrogen, carbon monoxide, and unburned hydrocarbons are expressed as grams of nitrogen dioxide ( $\text{NO}_2$ ), carbon monoxide (CO), and  $\text{CH}_2$  per kilogram of fuel, respectively.

Carbon dioxide concentrations in the gas samples were determined, and fuel-air ratios calculated from a carbon balance agreed to within 15 percent with values obtained from fuel-flow and airflow-rate measurements. Thus, representative exhaust-gas samples were obtained with the stationary probe.

### Smoke Number Measurement

Smoke samples were obtained according to the procedure recommended in reference 4 by withdrawing exhaust gases through the probe while it traversed the combustor exit (fig. 1). The sample flow rate at standard conditions was 236 cubic centimeters per second. Smoke numbers determined with the smoke meter described in reference 1 are based on 1.623 grams of gas per square centimeter of filter tape. A reflective den-

sitometer was used to measure comparative reflectance of the smoke stain, and a Welch Gray Scale was used for instrument calibration.

### Calculations

The U.S. customary system of units was used in primary measurements. Values were converted to SI units (Système International D'Unités) for reporting purposes only. When the conversions were made, consideration was given to implied accuracy, so that some of the values expressed in SI units were rounded off.

Pattern factor. - The pattern factor  $\bar{\delta}$  is defined by the expression

$$\bar{\delta} = \frac{T_{\max} - T_{\text{av}}}{\Delta T}$$

where  $T_{\max}$  is the highest local combustor exit temperature, and  $\Delta T$  is the average combustor temperature rise.

For calculations of temperature distribution parameters, non-mass-weighted temperatures were used. Approximately 10 percent of the temperature readings at each combustor side wall were disregarded to eliminate the side wall effects, which are always present in sector tests.

Smoke number. - The smoke number, as defined in reference 4, was determined from the following expression:

$$\text{Smoke number} = 100 (1 - r)$$

where  $r$  is the ratio of the percent of absolute reflectivity of the smoke stain to that of the clean filter paper.

### RESULTS AND DISCUSSION

To compare the durability of the four differently shaped fuel nozzles, Jet A fuel was burned in the combustor over a fuel-air-ratio range of 0.008 to 0.018 at a reference velocity of 21.3 meters per second and at the combustor inlet-air conditions given in table I. Fuel nozzle durability was determined after a total of 56 hours of testing.

## Fuel Nozzle Performance

Fuel nozzle temperatures were measured to indicate the ability of each nozzle to withstand the conditions encountered in a high-pressure combustor operating at high inlet-air temperatures and pressures. Also, after 56 hours of testing, the fuel nozzles were photographed and examined for erosion damage.

Fuel nozzle temperatures. - As shown in figure 6(a), the blunt-tip nozzle had the lowest temperature of approximately 700 K. The flat-tip and conical-tip nozzles were also below the inlet-air temperature of 811 K. However, the cylindrical-tip nozzle previously used in reference 1 was much higher in temperature, nearly 1300 K at a fuel-air ratio of 0.010. These data were obtained during the first 8 hours of the overall 56 hours of durability testing, at an inlet-air pressure of 41 newtons per square centimeter and a reference velocity of 21.3 meters per second.

After an additional 40 hours of testing at inlet-air pressures and temperatures of 41 to 203 newtons per square centimeter and 477 to 700 K, respectively, the initial 8-hour run was repeated in the final 8 hours of testing at the same test conditions. Nozzle temperature data for this run are shown in figure 6(b). Only the flat-tip nozzle temperature remained below the inlet-air temperature of 811 K at a fuel-air ratio of 0.010. The temperature of the cylindrical-tip nozzle had decreased approximately 300 K, whereas the temperatures of the conical-tip and blunt-tip nozzles had increased 170 and 130 K, respectively. Although the flat-tip nozzle had a temperature increase of 50 K in the final tests, it showed the best thermal stability of all of the nozzles. This temperature increase of 50 K was attributed to a small accumulation of carbon on the flat-tip nozzle.

Fuel nozzle erosion and carbon formation. - Photographs of the four fuel nozzles taken after 56 hours of durability testing are shown in figure 7. Of the four shapes of splash-cone fuel nozzles, the flat-tip design (fig. 7(a)) experienced the least erosion and was only slightly susceptible to carbon formation. In comparison with the cylindrical-tip nozzle (shown in fig. 7(b) and previously used in ref. 1), the flat-tip shape represents a considerable improvement in splash-cone nozzle design, since the cylindrical-tip nozzle showed extensive erosion damage. Also, the erosion damage to the conical-tip and blunt-tip nozzles (figs. 7(c) and (d), respectively) indicates that they too are unacceptable as compared with the flat-tip nozzles.

Exit temperature profiles. - A comparison of combustor exit temperature profiles obtained in the initial and the final 8 hours of durability testing is shown in figure 8. Although the exit temperature profile did not change appreciably with deterioration of three of the nozzles, the pattern factor increased markedly from 0.29 to 0.63. To explain this increase in pattern factor, local temperatures measured during the traverse were checked. At points directly downstream from the conical-tip and cylindrical-tip



nozzles, temperatures considerably above the average exit temperature were observed. These high temperatures were attributed to deterioration of the conical-tip and cylindrical-tip nozzles, which in turn caused streaking of the flame and the marked increase in the pattern factor.

### Exhaust Emissions From Durability Tests

Effect of inlet-air temperature on exhaust emissions. - As shown in figure 9, the exhaust emission data obtained for individual runs during the first half of the 56-hour durability test period did not differ appreciably from those obtained for individual runs during the final half of the test period. Thus, the deterioration of three of the nozzles did not make an appreciable difference in the exhaust emissions. However, as shown in figure 9(a), the  $\text{NO}_x$  emission index of approximately 5 (which was an average value obtained for the four nozzles operating simultaneously) was considerably below the value of 9 given in reference 1 for cylindrical-tip nozzles at an inlet-air temperature of 600 K. The CO emission index at the simulated idle inlet-air temperature of 500 K, shown in figure 9(b), was approximately the same as that given in reference 1 and dropped considerably below reference 1 values at 800 K. The unburned-hydrocarbon emission index at simulated idle conditions was also approximately the same as the reference 1 value of 3.5 and dropped considerably below the reference 1 value at 800 K, as shown in figure 9(c).

Effect of inlet-air pressure on oxides-of-nitrogen emission index. - The increase in  $\text{NO}_x$  emission index with increasing inlet-air pressure at an inlet-air temperature of 589 K is shown in figure 10. Initially, at 40 newtons per square centimeter,  $\text{NO}_x$  values were nearly 50 percent below those given in reference 1. However, at 200 newtons per square centimeter, the  $\text{NO}_x$  value was 13, as compared with the value of 8 given in reference 1. Erosion of three of the nozzle shapes adversely affected  $\text{NO}_x$  emissions at high inlet-air pressure.

### Exhaust Emissions With Flat-Tip Nozzles

Since the flat-tip design gave the best durability results, four flat-tip fuel nozzles were installed in the combustor. Emission indices for  $\text{NO}_x$ , CO, and unburned hydrocarbons and smoke number were determined over the range of operating conditions given in table II.

Effect of inlet-air temperature on exhaust emissions. - As shown in figure 11(a), the  $\text{NO}_x$  emission index was reduced about the same with flat-tip nozzles as with the

four differently shaped nozzles tested simultaneously in the combustor. In comparison with values for cylindrical-tip nozzles used in reference 1, the  $\text{NO}_x$  emission index was reduced from 9 to 5, or approximately 45 percent, at an inlet-air temperature of 600 K. Thus, at this condition a reduction in  $\text{NO}_x$ , as well as improved durability, was obtained with flat-tip nozzles as compared with cylindrical-tip nozzles. However, at the idle condition (480 K), the CO and unburned hydrocarbon emission indices of 44 and 16, respectively, were somewhat higher for the flat-tip nozzles than those for cylindrical-tip nozzles or the four differently shaped nozzles (figs. 11(b) and (c)).

Effect of inlet-air pressure on oxides-of-nitrogen emission index. - Increases in  $\text{NO}_x$  emission index with increasing inlet-air pressure at inlet-air temperatures of 700 and 589 K are shown in figure 12. At an inlet-air pressure of 200 newtons per square centimeter, the  $\text{NO}_x$  emission index was approximately 10 for both flat-tip and cylindrical-tip nozzles and approximately 13 for the four differently shaped nozzles. At an inlet-air pressure of 40 newtons per square centimeter, the  $\text{NO}_x$  emission index for flat-tip nozzles was approximately 4. This value is nearly 50 percent lower than that for cylindrical-tip nozzles but is approximately the same as that obtained with the four differently shaped nozzles. Thus, the flat-tip shape was the best design for splash-cone nozzles on the basis of low  $\text{NO}_x$  emissions as well as durability. At a combustor operating condition of 700 K and 101 newtons per square centimeter, the flat-tip nozzles gave a  $\text{NO}_x$  emission index of 12.

Effect of fuel-air ratio on exhaust smoke number. - Exhaust smoke number increased with increasing fuel-air ratio, as shown in figure 13. Smoke numbers for the two types of nozzles did not differ appreciably. At an inlet-air temperature of 700 K and pressure of 101 newtons per square centimeter and a fuel-air ratio of 0.018, the smoke number for the set of four flat-tip fuel nozzles was approximately 18.

## SUMMARY OF RESULTS

Fuel injector erosion damage was simultaneously determined for four designs of splash-cone fuel nozzles installed in a combustor segment and durability tested for 56 hours. Jet A fuel was injected at fuel-air ratios of 0.008 to 0.018 and inlet-air temperatures and pressures up to 811 K and 203 newtons per square centimeter, respectively. Variations in fuel nozzle temperature and exit temperature profile were measured, and exhaust emission indices for oxides of nitrogen, carbon monoxide, and unburned hydrocarbons were determined. Also, combustor tests were made in which exhaust emissions and smoke numbers were determined with a set of four flat-tip fuel nozzles. The following results were obtained:

1. A flat-tip splash-cone fuel nozzle showed the least erosion damage with good

flame stabilization and was least susceptible to carbon accumulation as compared with cylindrical-, conical-, and blunt-tip designs.

2. At an inlet-air temperature of 811 K, the flat-tip nozzle metal temperature remained 20 to 120 K below the inlet-air temperature throughout the tests, whereas the metal temperature of the cylindrical-tip nozzle was initially as high as 1285 K.

3. Extensive deterioration of the cylindrical-, conical-, and blunt-tip nozzles did not appreciably change the exhaust emissions.

4. The oxides-of-nitrogen emission index was approximately 12 at a combustor operating condition of 700 K and 101 newtons per square centimeter with flat-tip nozzles, and the smoke number was within the visibility limit of  $25 \pm 5$ .

5. At simulated idle conditions of 477 K and 41 newtons per square centimeter, emission indices for carbon monoxide and unburned hydrocarbons were 44 and 16, respectively, with flat-tip nozzles.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, October 1, 1974,  
505-03.

#### REFERENCES

1. Ingebo, Robert D.; and Norgren, Carl T.: High Pressure Combustor Exhaust Emissions With Improved Air-Atomizing and Conventional Pressure-Atomizing Fuel Nozzles. NASA TN D-7154, 1973.
2. Ingebo, Robert D.; Daskocil, Albert J.; and Norgren, Carl T.: High-Pressure Performance of Combustor Segments Utilizing Pressure-Atomizing Fuel Nozzles and Air Swirlers for Primary Zone Mixing. NASA TN D-6491, 1971.
3. Procedure for the Continuous Sampling and Measurement of Gaseous Emissions From Aircraft Turbine Engines. Aerospace Recommended Practice 1256, SAE, Oct. 1971.
4. Aircraft Turbine Exhaust Smoke Measurement. Aerospace Recommended Practice 1179, SAE, May 1970.

TABLE I. - COMBUSTOR CONDITIONS FOR  
NOZZLE DURABILITY TESTS

[Fuel-air ratio, 0.008 to 0.018; reference velocity,  
21.3 m/sec; total test time, 56 hr.]

| Test period  | Duration of<br>test period,<br>hr | Inlet-air<br>pressure,<br>N/cm <sup>2</sup> | Inlet-air<br>temperature,<br>K |
|--------------|-----------------------------------|---|--------------------------------|
| Initial      | 8                                 | 41  | 811                            |
| Intermediate | 20                                | 41  | 477, 589, 700                  |
|              | 10                                | 101   | 589, 700                       |
|              | 10                                | 203   | 589, 700                       |
| Final        | 8                                 | 41  | 811                            |

TABLE II. - COMBUSTOR CONDITIONS  
FOR FLAT-TIP NOZZLE TESTS

[Fuel-air ratio, 0.008 to 0.018; reference  
velocity, 21.3 m/sec.]

| Inlet-air pressure,<br>N/cm <sup>2</sup> | Inlet-air temperature,<br>K |
|--|-----------------------------|
| 41                                       | 477, 589, 700, 811          |
| 101                                      | 589, 700                    |
| 203                                      | 589, 700                    |

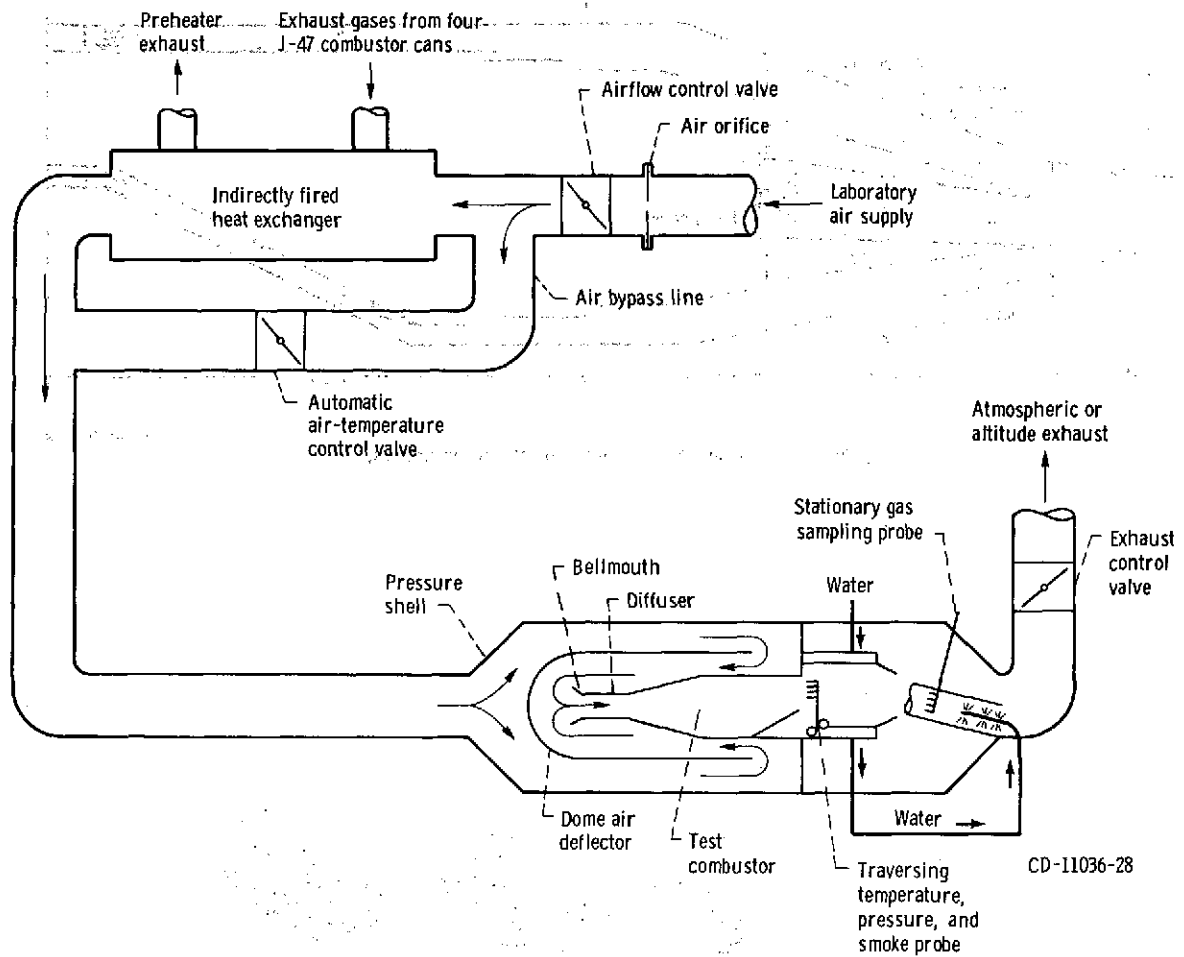


Figure 1. - Test facility and auxiliary equipment.

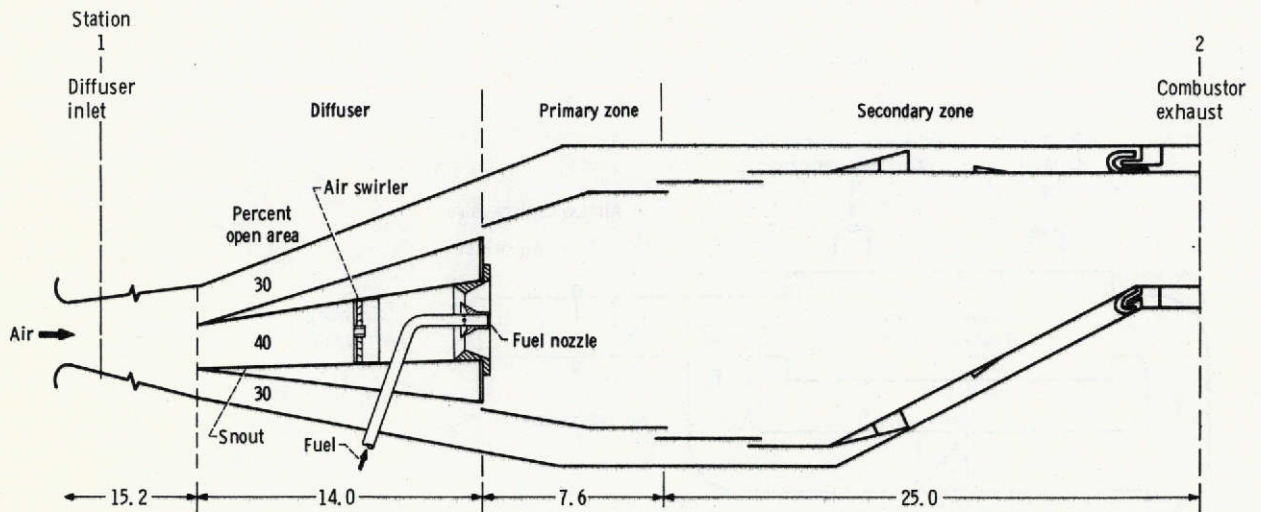
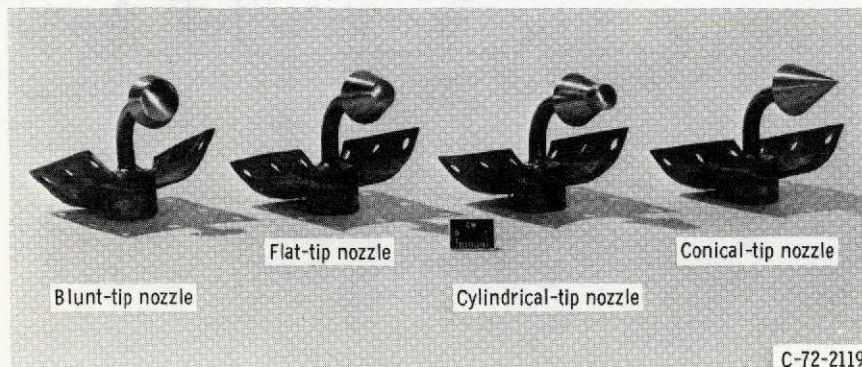


Figure 2. - Test combustor. (Dimensions are in centimeters.)

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Figure 3. - Air-atomizing splash-cone fuel nozzles mounted on fuel tubes.



⊗ Thermocouple  
(embedded in nozzle)

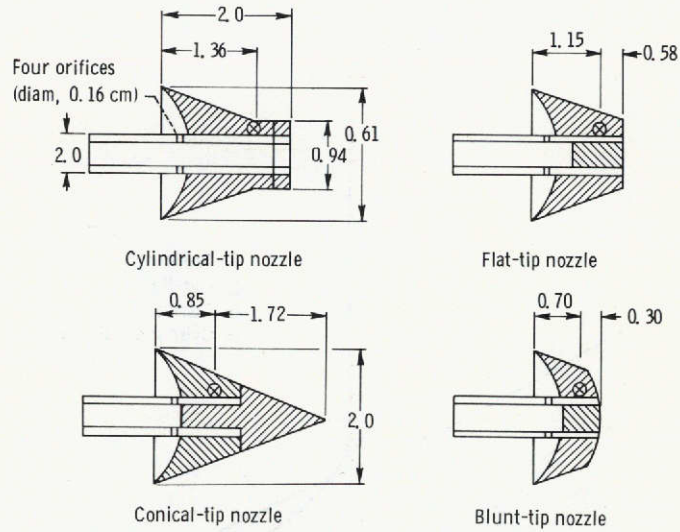


Figure 4. - Schematic diagram of fuel nozzles and thermocouple locations.  
(Dimensions are in centimeters.)

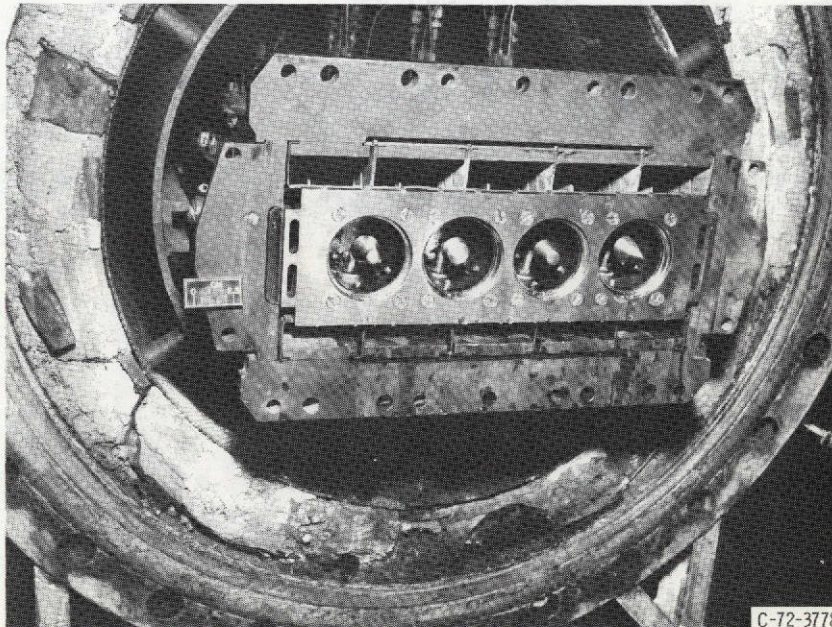


Figure 5. - View (looking upstream) of fuel nozzles installed in combustor.

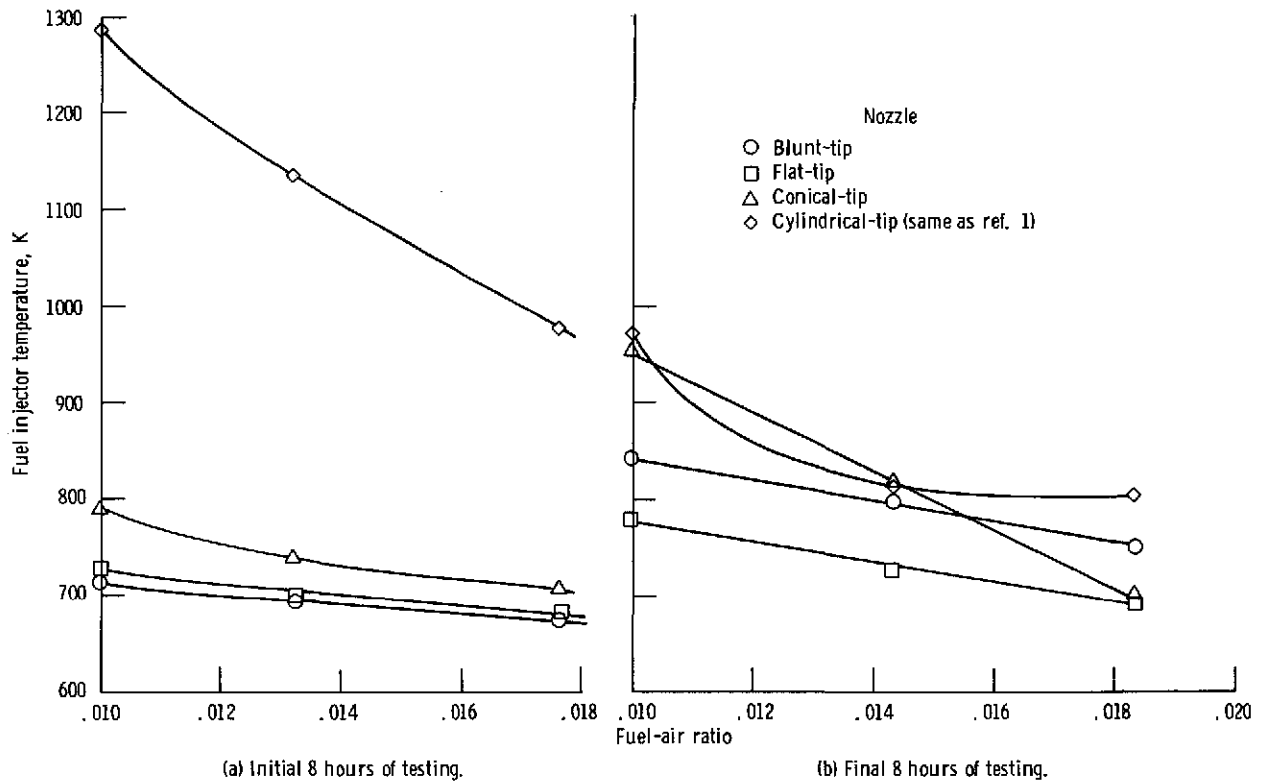
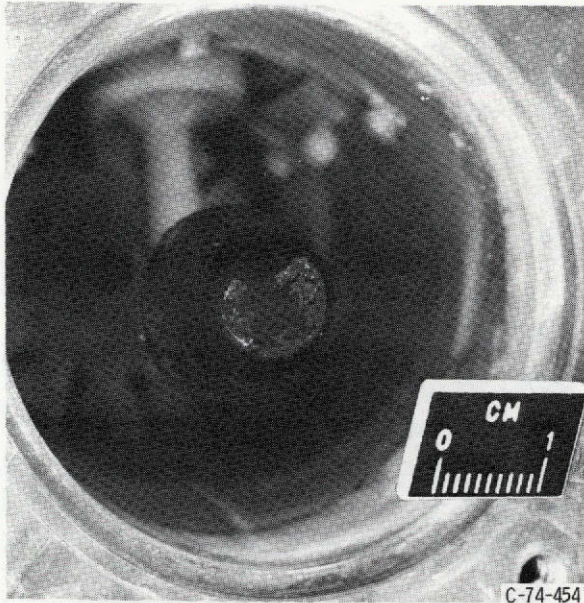
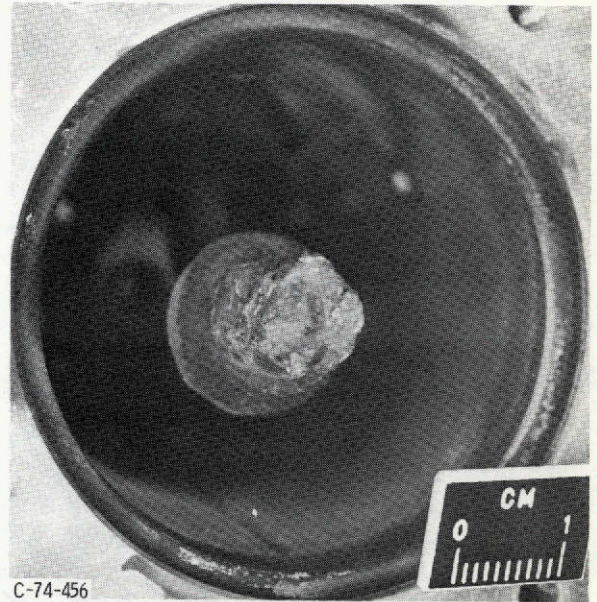


Figure 6. - Variation of fuel injector temperature with fuel-air ratio for four nozzle shapes. Inlet-air temperature, 811 K; inlet-air pressure, 41 newtons per square centimeter; reference velocity, 21.3 meters per second.

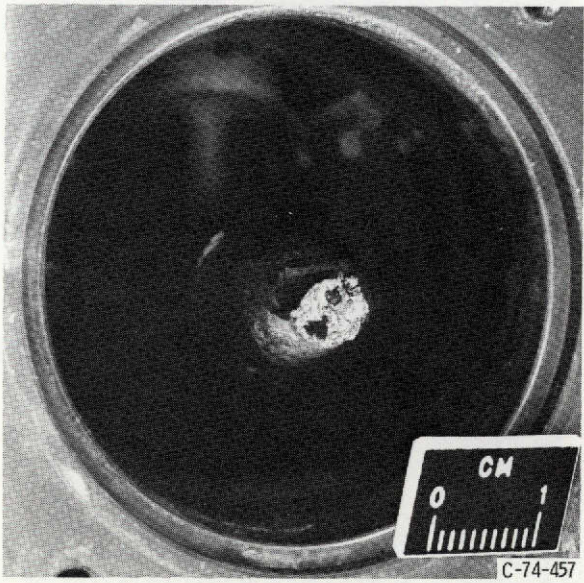




(a) Flat-tip nozzle.



(b) Cylindrical-tip nozzle.



(c) Conical-tip nozzle.



(d) Blunt-tip nozzle.

Figure 7. - Air-atomizing splash-cone fuel nozzles after 56-hour durability test.

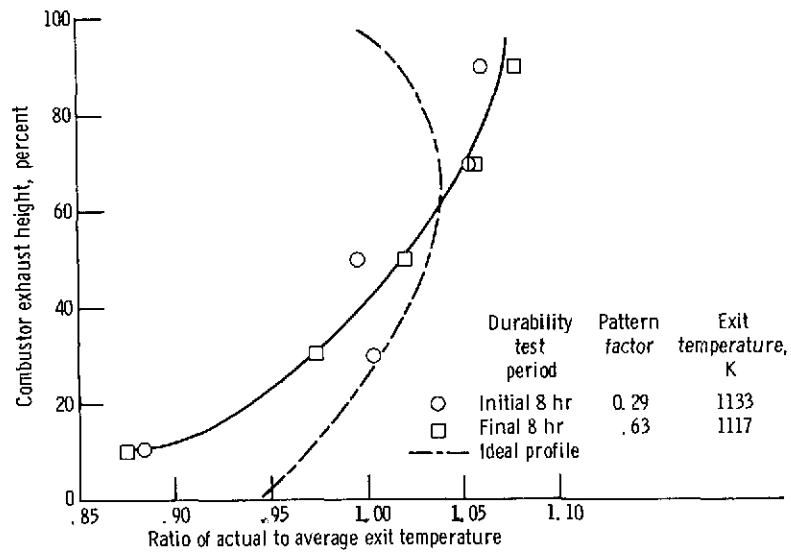


Figure 8. - Comparison of initial and final combustor exit temperature profiles obtained with nozzles of four shapes operating simultaneously.

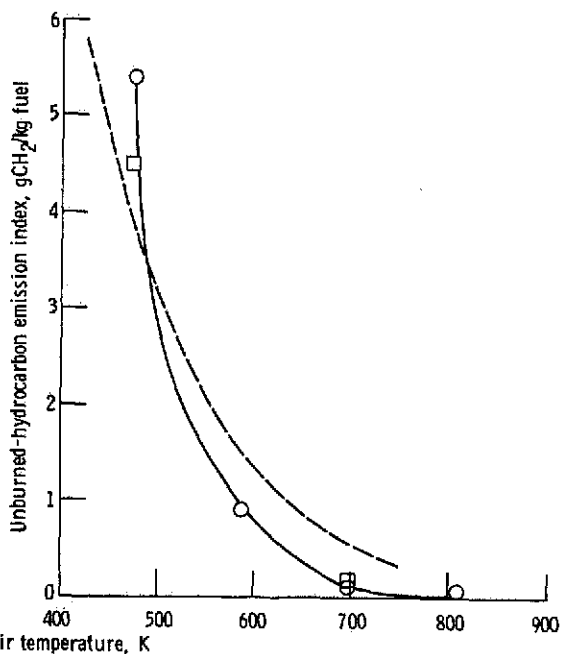
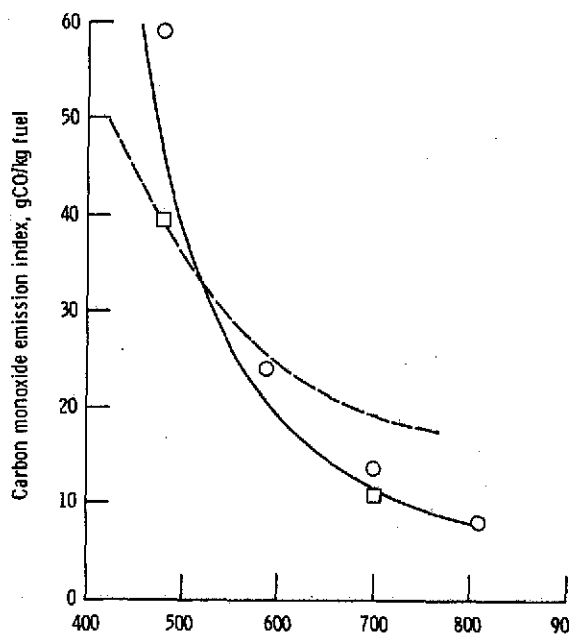
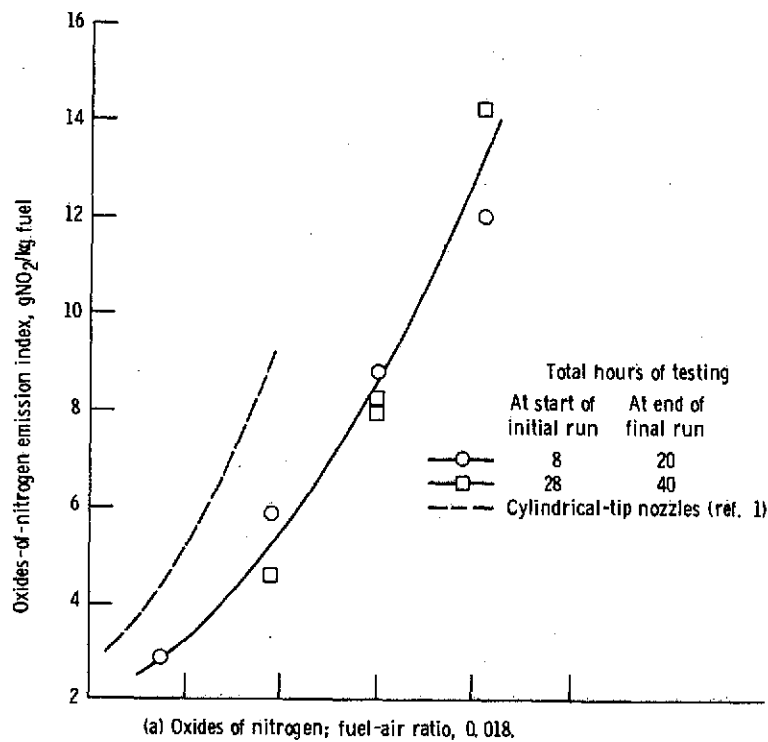


Figure 9. - Effect of inlet-air temperature on exhaust emissions during durability tests with nozzles of four shapes operating simultaneously. Inlet-air pressure, 41 newtons per square centimeter; reference velocity, 21.3 meters per second; duration of tests, 12 hours.

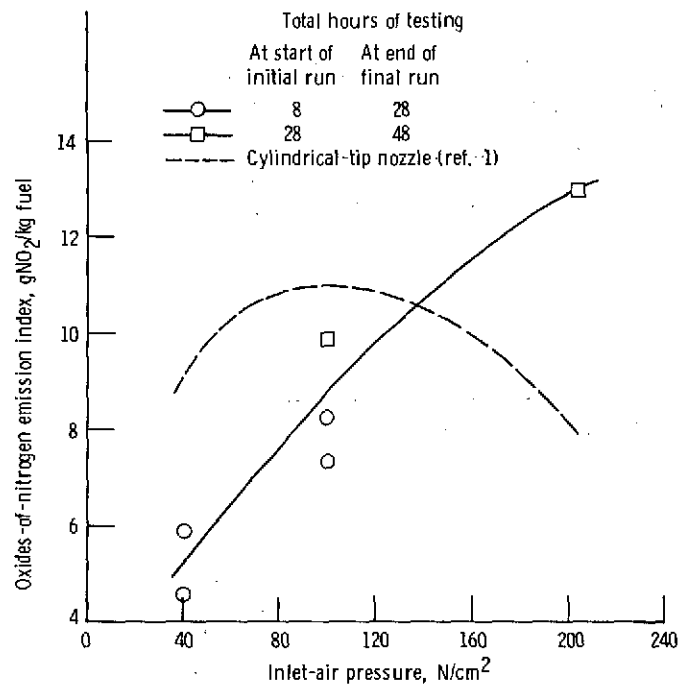


Figure 10. - Variation of oxides-of-nitrogen emission index with inlet-air pressure during durability tests with nozzles of four shapes operating simultaneously. Inlet-air temperature, 589 K; fuel-air ratio, 0.018; reference velocity, 21.3 meters per second; duration of tests, 20 hours.

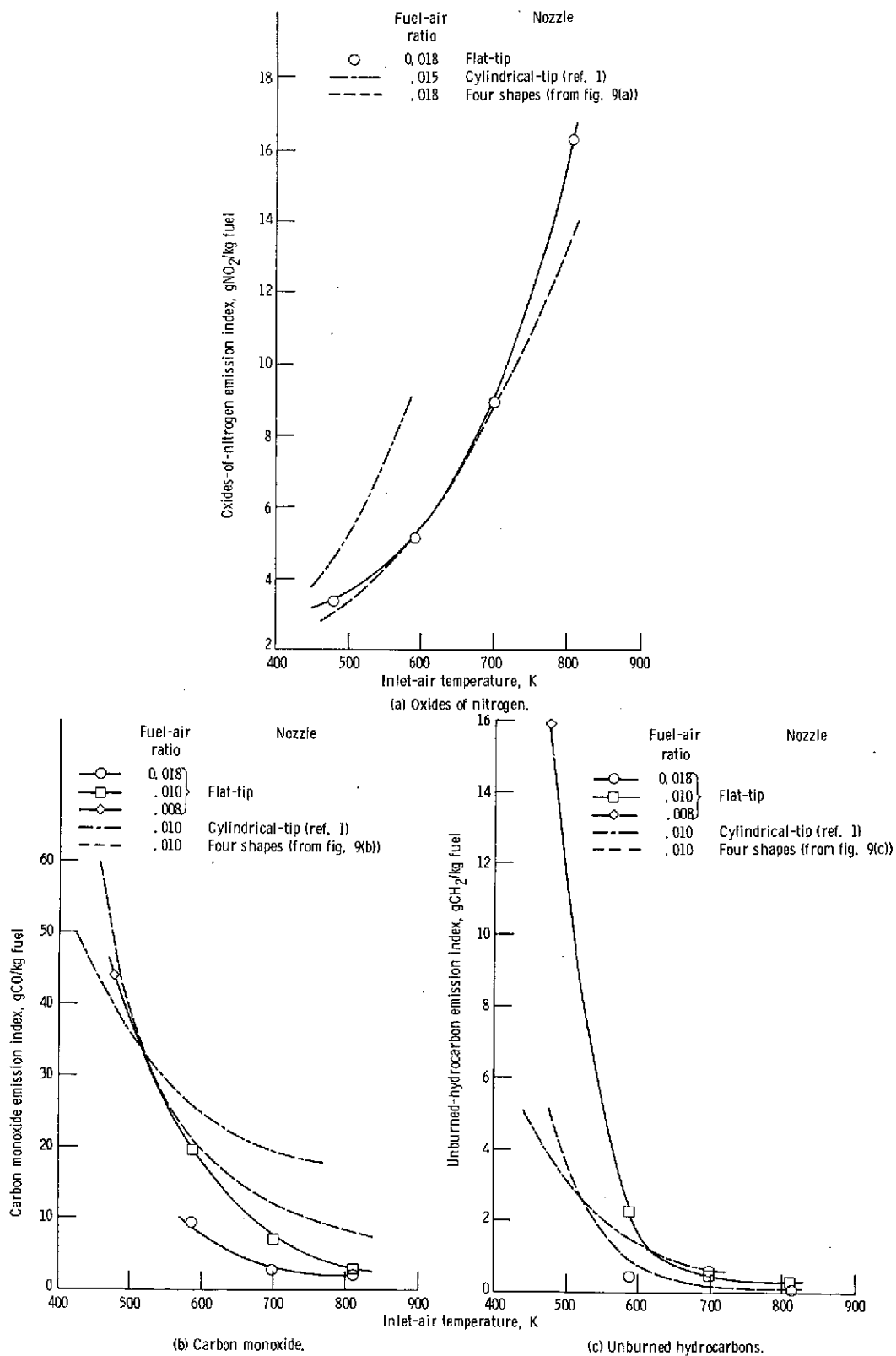


Figure 11. - Effect of inlet-air temperature on exhaust emissions for set of four flat-tip nozzles. Inlet-air pressure, 41 newtons per square centimeter; reference velocity, 21.3 meters per second.

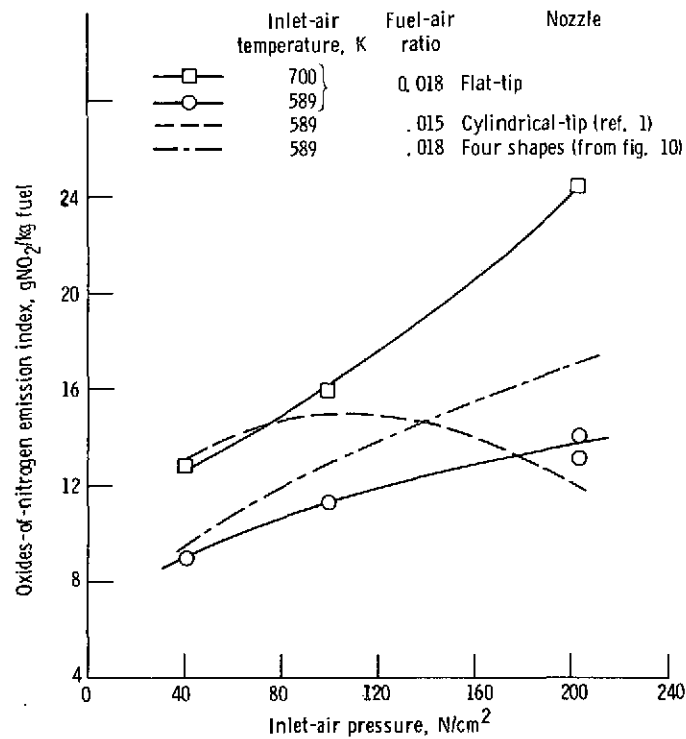


Figure 12 - Variation of oxides-of-nitrogen emission index with inlet-air pressure for set of four flat-tip nozzles. Reference velocity, 21.3 meters per second.

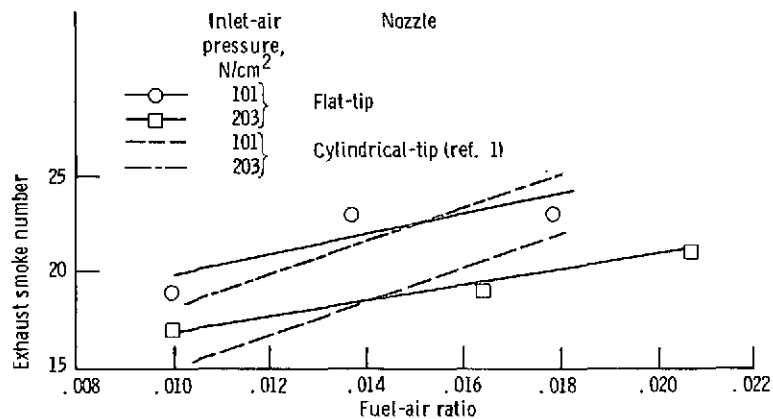


Figure 13 - Variation of exhaust smoke number with fuel-air ratio. Reference velocity, 21.3 meters per second; inlet-air temperature, 700 K.